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The Marco Polo mission: a sample return from a low-albedo Near Earth Object in the ESA Cosmic Vision Program 2015-2025

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ABSTRACT

Marco Polo is a sample return mission to a Near-Earth Object (NEO) which was originally proposed as a joint European-Japanese mission for the scientific program Cosmic Vision 2015-2025 of the European Space Agency (ESA) in June 2007 and selected for an assessment study until fall 2009. The main goal of this mission is to return a sample from a dark taxonomic type (low albedo) NEO for detailed laboratory analysis in order to answer questions related to planetary formation, evolution and the origin of Life. In addition, it will provide detailed information on the physical

and chemical properties of a body belonging to the population of potential Earth impactors, and therefore it is also directly relevant to the problems of risk assessment and mitigation. We review basic information on NEOs, potential targets for a sample return mission and the Marco Polo mission, with emphasis on their relevance to impact risk assessment and mitigation. More details on the Marco Polo mission and scientific objectives can be found in [1].

INTRODUCTION

The NEO population includes both asteroids and comet nuclei on orbits with perihelion distances $q \leq 1.3$ AU. Thus, they periodically approach or intersect the Earth's orbit. The median lifetime of the NEO population is about 9 Myr [2] although the number of objects is believed to be constant on average. Indeed, the chronology of craters up to 3.8 Gyr on the Moon, which was calibrated by counting the craters and dating the samples brought back by the Apollo missions, indicates that the flux of impactors has been kept constant during the last 3.8 Gyr, with some fluctuations due to stochastic events such as the formation of an asteroid family. Therefore, NEOs must be continuously replenished from major small body reservoirs. Reference [3] identified four major sources of NEOs, three of which are located in the asteroid main belt and one associated with Jupiter Family Comets. NEOs are therefore representative of asteroids and comets which are the remnants of the primitive leftover building blocks (planetesimals) of Solar System formation processes. Several thousand NEOs are currently known, but the whole population seems to contain somewhat more than 1000 objects with diameter larger than 1 km and hundreds of thousands greater than 100 m [4, 5]. Our knowledge of the structure and composition of NEOs is still rather limited, since only a few percent of the known NEOs have diagnostic spectral or photometric observations. Their most important characteristic is the high degree of diversity in terms of physical properties. Some objects have very elongated shapes, others have complex, non-principal axis rotation states, both very long and very short rotational periods are observed, and binary systems represent as much as 15% of the whole population. The NEO diversity is also emphasized by the different taxonomic types found within the population: all the taxonomic classes present among main belt asteroids are recognized among NEOs. The taxonomic classification of NEOs can give some hints about the regions of the Solar System where these objects come from: E- S- and Q-types from the inner main-belt region, C-types from the mid to outer belt, P-types from the outer belt, and D-types seem to be at least partially related to the Jupiter family comets. The dark taxonomic type (albedo <0.1) asteroids, such as C, D, P and related types, are considered to be composed of the most primordial materials (based on meteorite analogues) and therefore to be more primitive than bright taxonomic type (albedo >0.1) objects, such as S or E types.

The study of the physical nature of NEOs is relevant to the potential hazard posed to our planet. NEOs are responsible for most meteorite falls and of the occurrence of occasional major catastrophic impact events. Whatever the scenario, it is clear that the technology needed to set up a realistic mitigation strategy depends upon knowledge of the physical properties of the impacting body. In particular, deflecting a body using a kinetic impactor depends on the response of the body to the impact, which in turns depends on its physical properties. Using the concept of a gravitational tractor also requires a precise determination of the mass, shape and rotation state of the object.

PREVIOUS NEO RENDEZVOUS MISSIONS

The NASA NEAR Shoemaker mission performed a complete investigation of the 23 km-sized NEO (433) Eros during a one-year orbital survey in 2000 [6]. The Japanese Hayabusa mission reached the 500 meter-sized NEO (25143) Itokawa in fall 2005 and attempted to take a sample in addition to hovering during 3 months close proximity to the object [7]. Both missions, thanks to their in-situ measurements, improved greatly our knowledge of the physical properties of these objects. In particular, Hayabusa provided the first detailed data concerning a NEO in the size range similar to that expected for the threatening object Apophis (a few hundred meters). The images of Itokawa (see Fig. 1) and its low bulk density (about 1.9 g/cm³) suggest that this body is not a monolithic object but rather a rubble pile composed of blocks which re-accumulated after the disruption of its parent body, a scenario which was first discovered by numerical simulations of catastrophic disruptions [8]. Fig. 1 shows that the surface is composed of many such blocks and that the shape is highly irregular. Assuming that such an object was on a collision course with the Earth, our ability to deflect it needs to be demonstrated.

At a European level, ESA proposed in 2007 a preparation initiative for a sample return space mission to a NEO, inserting direct laboratory analysis of NEO samples among the major topics to be investigated in the Cosmic Vision 2015-2025 timeframe. In this context, a joint European-Japanese proposal of a sample return mission to a primitive NEO, named Marco Polo, was established. Marco Polo passed the first stage of selection in October 2007 for a two-year

assessment study. Final mission selection will be in 2011 with launch in the mid-2010s. Note that both targets of the two previous space missions were S-type objects, and therefore, to have a good knowledge of the different impactor types, detailed observations of a NEO belonging to a primitive class still need to be performed and should also be a priority in the framework of mitigation studies.

POTENTIAL TARGET CANDIDATES FOR THE MARCO POLO MISSION

NEOs evolve on a wide range of orbits, and not all of them can be reached easily from Earth. A key constraint is the velocity change (ΔV) needed to realize a rendezvous and Earth return mission (in the case of a sample return mission, another one is the re-entry velocity in Earth's atmosphere). Target candidates are required to need a low ΔV to reach them, and therefore it is no big surprise that their orbits make them potential Earth impactors. Indeed, Eros and Itokawa have been found to have a non-zero probability of collision with the Earth on million-year timescales [9, 10]. Thus a sample return mission to a NEO not only allows us to address fundamental questions related to planetary formation, but because the target is necessarily constrained to be among the ones which can come close to Earth, it contributes to a better knowledge of a potentially threatening object. Table 1 lists the best dark-type target candidates (the primary objective for Marco Polo) in terms of ΔV and other properties for such a space mission. Such targets are also relevant for mitigation studies because they are believed to contain some fraction of porosity, as indicated by the low bulk density estimated for some of them (notably estimated about 1.3 g/cm^3 , as measured for (253) Mathilde during the fly-by of the NEAR probe in 1997 [11]). Our current understanding of the collisional process on porous materials indicates that these bodies can dissipate a higher fraction of the impact energy compared to non-porous ones, in particular when they contain porosity at micro-scale, as part of the energy goes into the crushing of pores. Therefore, craters can be produced by compaction, which may explain the presence of 5 craters larger than 20 km in diameter on the 52-km Mathilde surface. This is the worse case scenario for a deflection using a kinetic impactor as the efficiency of the transfer of momentum highly depends on the amount of ejecta from the crater produced by the impactor. If the production of the crater is due to compaction instead of excavation of material, the deflection will be minimized. This demonstrates the importance of having a better knowledge of the physical properties of this class of objects, which can help us better estimate their impact response. This knowledge can also help us better characterize the magnitude of the Yarkovsky thermal effect by using measured material parameters, and therefore take it into account with higher accuracy in the dynamical evolution of NEOs. This is a crucial point as, for instance, the likelihood that the asteroid (99942) Apophis will go through the identified keyhole during its encounter with the Earth in 2029, and then impact our planet in 2036, cannot be assessed with great accuracy at least partially because the Yarkovsky effect is not well characterized for this object. Measuring the material parameters that are needed as input to model this effect would greatly improve impact predictions.

The other constraints regarding the target are that:

- i) its gravity is high enough to allow the determination of the gravity field with sufficient accuracy to provide some constraint on the internal structure (e.g. determine the J_2 coefficient to 10 %).
- ii) it is bright enough for fundamental properties (size, shape, albedo, rotation) to be estimated from ground-based observations.

As no precise numbers can currently be given for the above points, for the purpose of the mission study a minimum absolute visual magnitude of $H \leq 21 \text{ mag}$ is assumed, corresponding to a diameter $D \geq 340 \text{ m}$ for a representative dark-type body assuming a visual geometric albedo of 0.06. It is thus likely that the target will have a size in the range that can cause at least regional or global damage during an impact on Earth (from a few hundred meters, like Apophis, to kilometer size).

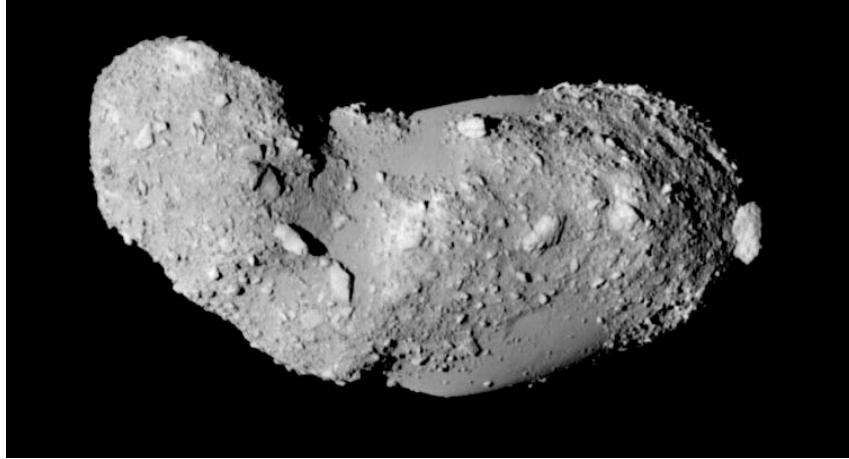


Fig. 1: Image of the small S-type NEO Itokawa (about 500 m) observed by the Japanese spacecraft Hayabusa in 2005.

The shape of the object is highly irregular, large boulders are present on its rough surface and its low bulk density implies a high fraction of porosity (about 41%) assuming that LL chondrites are reasonable analogs of its composition.

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Then, to properly perform mission planning, it is important that both the asteroid size and shape are known at least roughly. Also, its rotation period must be known. If it rotates too quickly, it will be difficult to approach one particular point on the surface and complete the sampling activity without coming onto the night side of the object. Additionally, very fast rotators may have ejected their loose regolith and consist of competent rock surface only. Thus, fast rotators should be avoided and we require a minimum rotation period of ~ 2.5 hours. There is no strong scientific requirement for an upper limit to rotation period. However, as was shown in the internal ESA study of the mission, the longer the rotation period, the longer it will take to map the complete asteroid from orbit. We thus require that the rotation period should not exceed 5 days. Table 1 indicates a list of potential targets that comply with these constraints.

THE MARCO POLO MISSION: SCIENTIFIC REQUIREMENTS

As part of the mission study, a so-called Study Science Team was formed, both on the Japanese and on the European side. For the European studies, a Science Requirements Document [12] was written. The following sub-sections provide a top-level summary of these science requirements. Note that at the current phase of the study, the science requirements for the ground-based analyses of the sample are not yet given in detail, so the focus lies on the science requirements of the space segment. Recall that the ultimate goal of the mission is to return a sample for laboratory analysis, so many requirements concentrate on this aspect. Here, we emphasize those that are of interest for risk assessment. Three phases are thus considered:

- ‘Global characterisation’ means to measure the properties of the whole NEO, on a global scale;
- ‘Local characterisation’ is the characterisation of up to 5 dedicated areas which are identified as potential sampling sites;
- ‘Sample context’ are measurements being performed at the actual sampling site.

Table 2 gives an overview of the required orders of measurement resolution for the different scenarios.

Table 1: list of potential targets for the mission Marco Polo. The size is calculated from the absolute magnitude, assuming an albedo of 0.06. In the case of the binary 1996FG3, the rotation period is given for the primary.

Object	Taxonomic Type	Estimated size (km)	Rotation Period (h)
2001 SK162	T	1.52	68
2001 SG286	D	0.35	unknown
1989 UQ	C	0.76	7.7
1996 FG3	C, binary	1.4 and 0.43	3.6
1999 JU3	Cg	0.78	7.7
4015 Wilson-Harrington	C, Dormant Comet	3.5	6.1

Table 2: Resolution requirements for global characterisation, local characterisation, and context measurements.

	Spatial resolution for imaging in the visual	Spatial resolution for VIS/IR spectrometer	Spatial resolution for mid-IR instrument
Global characterisation	Order of dm	Order of m	Order of 10 m
Local characterisation	Order of mm	Order of dm	Order of dm
Context measurements	Tens of μm	-	-

Global Characterisation

‘Global characterisation’ means to measure the properties pertaining to the entire NEO at a global scale. Such measurements are obviously important for mitigation purposes but so far, have only been made from space for two S-type asteroids, and therefore, our knowledge of these properties for dark-types is still very poor.

Imaging Requirements

For Marco Polo, it is required that the complete surface of the NEO will be imaged in at least three different colors in the visible range with a spatial resolution of the order of decimeters, and with local solar elevation angle between 30 and 60°. This solar elevation will avoid extensive shadowing of some of the surface regions, but give enough shadows to properly determine craters, boulders, and other surface features.

Spectroscopy

The complete surface of the NEO shall be imaged in the visible and near-IR wavelength range from 0.4 to 3.3 μm with a spectral resolution of at least $\lambda/\Delta\lambda$ in the order of 200 and a spatial resolution of the order of meters to characterise the mineral properties of the surface. If there are areas which are never illuminated it may not be possible to map them. However, the mid-IR observations will also return good results on the dark side of the object, and they may even be beneficial for the measurement of the thermal characteristics of the object.

Mass, Size and Shape

The precise determination of the size, shape and rotation period/axis of the object is included in the global characterisation. Once the size and shape is precisely known, measurements of the spacecraft movement will allow the determination of the mass of the object, plus possibly higher-order terms of the gravity field. The accuracy on the mass estimate should be about 1%. After some analysis, we also require that the shape model must be obtained with an accuracy of typically 1 m in height and spatial resolution with respect to the center of mass (in both illuminated and non-illuminated regions). The spatial resolution of the local topography (*i.e.* in relative coordinates) should be determined to an accuracy of the order of decimeters.

Surface Temperature

To understand the evolution of the sample material over time, it is important to understand the thermal environment of the sample. In addition to minimum and maximum diurnal temperatures, determined from mid-IR observations, the thermal evolution during the ‘asteroid year’ and over its evolutionary history are important. The latter can only be addressed by statistical studies of the past history of the object. Observed temperatures and shapes allow construction of thermal models which are crucial to providing constraints on the magnitude of the Yarkovsky effect. For Marco Polo, we require that the surface temperature can be derived to an accuracy of at least 5 K (goal 1 K) at a spatial resolution of the order of 10 m at a number of rotational phases from which the thermal inertia can be determined to a precision of better than 10 %. From this, a more detailed measurement requirement is derived - the complete surface of the NEO shall be imaged in the mid-IR with a spatial resolution of the order of 10 m or better with a spectral resolution of at least $\lambda/\Delta\lambda$ in the order of 200 to determine the wavelength dependent emissivity, and hence identify mineral features in the range 8 – 16 μm (target 5 – 25 μm).

Local Characterisation

‘Local characterisation’ refers to up to 5 dedicated areas which are identified as potential sampling sites before the actual sampling. After a successful sampling, another local characterisation measurement cycle shall be performed to record any changes. The requirements for this cycle are structured in a similar way as for the global characterisation, but they only apply to an area of the size of the expected landing accuracy around the potential sampling sites, and with higher resolution. This information is also relevant for mitigation purposes, in particular to better assess the efficiency of momentum transfer by a kinetic impactor. Since in principle the shock wave generated by a cratering event does not go through the whole body, it is also important to have a better knowledge of the surface state and its vicinity on such a body.

Detailed requirements have been defined in relation to the sample. Here we only mention those which can be useful for mitigation purposes: the precise topography of the sampling site must be determined; this is foreseen to be done by imaging. Just as on the global scale, imaging is important for determining the geological context of the sample. We thus require imaging in the visible in at least three color filters, with a spatial resolution of the order of millimeters. Observations in the mid-IR can, as on the global scale, constrain the thermal properties of the surface but this time on a much smaller spatial scale. Local variations in *e.g.* the thermal inertia may allow assessment of the porosity of the regolith and its variation in the vicinity of the sampling site.

THE MARCO POLO MISSION STUDIED BY ESA

Strawman Payload

Most of the scientific requirements can be directly linked to a measurement technique such as imaging or spectroscopy. A ‘strawman payload’ has been defined as a baseline for the mission development [13]. It does not exclude additional instruments which may be included at a later stage of the mission, or even the deletion of instruments if they are deemed unnecessary.

The general rule for the internal ESA assessment study was to keep the payload as concentrated as possible on its main objective “To put the returned sample into global context”. This is different for the baseline JAXA-ESA mission (see below).

Example of Mission Scenario

The ESA-internal mission study concentrated on chemical propulsion; electrical propulsion would offer more flexibility in terms of target selection but, it was not considered for cost reasons. It is the baseline for the common JAXA-ESA mission. As an example, we present here a mission scenario to the C-type asteroid 1989 UQ. Four mission scenarios were actually studied [14]. ‘Mission 2017’ with GTO launch, which requires Earth and Venus swing-bys is described here. Instruments can be operated during these swing-bys to perform calibration measurements. One of the issues of this mission is that the satellite gets close to the Sun, requiring special care in designing the thermal control system to avoid overheating. Another issue is that a few weeks after arrival, the asteroid gets very close to the Sun as seen from the Earth, meaning that radio contact is difficult and critical operations have to be avoided. This mission would bring about 1700 kg mass to the asteroid. Table 3 shows the major milestones of ‘Mission 2017’.

Operational Activities at the NEO

In the ‘Mission 2017’, about 18 months are available at the asteroid target.. To structure the mission, several *mission phases* are introduced when in proximity to the NEO:

- Formation Flying or Far Global Characterisation (FAR)
- Terminator orbit (TER)
- Global characterisation (GLO)
- Local characterisation (LOC)

- Sampling and sample context measurements (SAM)
- Extended monitoring (EXT)

FAR: When arriving at the NEO, the spacecraft slowly approach the object. This first observation phase (FAR) will be performed from a safe distance to the object (around 5 km). The asteroid will rotate with respect to the spacecraft and most of the asteroid's surface will be visible. After a first assessment of the rotation axis position, it should be possible to move the s/c to a position optimizing the percentage of visible surface area. The position will be constrained from the balance between the asteroid gravity, the solar radiation pressure, and possibly the perturbing forces from other planets. It will be at the edge or outside the sphere of influence of the asteroid (see Fig. 2). The main objectives of the first observations will be to determine the precise rotational state of the asteroid, to produce a first shape model, and to derive a first mass estimate of the asteroid, all of which are particularly important for mitigation studies.

TER: The terminator orbit (TER) is an orbit where the perturbing forces are minimized, providing the best opportunity for detailed determination of the gravity field, which is the main goal of this phase lasting about one month. Note that due to solar radiation pressure on the spacecraft, it is expected that the orbit will be shifted from the terminator orbit, in a direction away from the Sun.

GLO: This is the main science orbit where the complete characterisation of the asteroid will be performed. The current assumption is that the spacecraft is in a "9-o'clock orbit", *i.e.* that the angle between the orbital plane and the plane through the asteroid – Sun line perpendicular to the asteroid orbital plane is 30°. Here, most of the science observations for global characterisation will be performed, including mapping in the visible and infrared wavelength bands. It is estimated that about 2 months are needed to get the coverage and resolution requirements.

LOC: The spacecraft will go close to the asteroid (typically 100 m distance) and use the remote sensing instruments to characterise the potential sampling sites. This will be done for up to 5 potential sampling sites. The spacecraft is assumed to stay still above the potential sampling site for the required duration of the measurement, currently assumed to be of the order of 10 minutes to one hour. This phase will have a duration of about 5 weeks.

SAM: This part is not described here as it is not directly relevant for mitigation studies.

EXT: If after the sampling the spacecraft has to wait to be able to return to Earth, the 'extended monitoring' can be done. Science measurements can be used to investigate long-term effects on the asteroid, for example:

- continue monitoring the asteroid with the IR instruments at regular intervals to study the thermal behavior of the asteroid at different solar distances;
- monitor the long-term behavior of particle sputtering from the asteroid surface;
- add data to get a higher-density grid of measurements with the Laser Altimeter;
- add image data to obtain more phase angle coverage and/or stereo information.

A COMMON JAXA-ESA MARCO POLO MISSION

The proposed scenario is to perform this mission in a collaborative effort between ESA and JAXA utilizing JAXA's experience with Hayabusa, scheduled to deliver its sample to Earth by June 2010 (although it is currently unclear if a significant sample has been collected). JAXA will provide the so-called 'mothership', which contains all required propulsion systems and the main sampling system and carries a separate Earth Return Capsule provided by ESA and a European Lander (possibly nationally-funded). A possible second sampling device could be provided by ESA. The payload will be provided by both partners. The main benefits over the previously described ESA study (as a result of the potentially higher budget) are the use of electrical propulsion providing a higher payload mass, the possibility of a separate lander, and a wider range of target accessibility. The choice of the target from the list mentioned previously will then depend on different constraints, such as the exact launch window suitable for both partners, and the design of the spacecraft. Note that new candidates may be discovered thanks to observational programs like PAN-STARRS.

Table 3: Mission timeline for 'Mission 2017'.

Launch window – on Soyuz Fregat launcher	2017 Aug 16 – 2017 Sep 06
Earth escape (delta-v = 3.492 km/s)	2017 Sep 20
Earth swing-by at 10906 km altitude	2018 Sep 20
Venus swing-by at 45534 km altitude	2019 Mar 05
Arrival at 1999 UQ, arrival mass ~1700 kg	2020 Dec 20
Departure	2022 Aug 04
Venus swing-by at 3076 km altitude	2023 Jun 24
Earth atmospheric entry with 4.17 km/s hyperbolic arrival velocity	2023 Nov 16

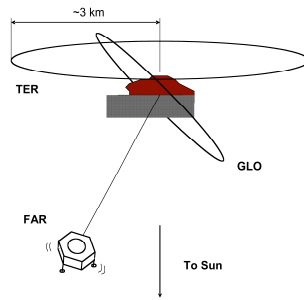


Fig. 2: Orbit configuration for the first mission phases.

CONCLUSIONS

The Marco Polo mission is the first sample return mission to a dark-type (believed to be primitive) asteroid officially selected by ESA for an assessment study. The global and local characterization of the target will provide crucial information to better define efficient mitigation strategies. The return of the sample for laboratory analysis will not only help answering questions related to planetary formation, but will also provide for the first time some knowledge of the material properties of a potential impactor of this type. Meteorites have suffered high stresses during their entrance into the atmosphere, and may not be representative of the material in space, as there is a strong bias toward the strongest materials that can survive such stresses. Numerical codes used for simulating asteroid impacts and deflections have up to now used material properties of terrestrial materials to model an asteroid, and they would greatly benefit from the measurements of properties of a real asteroid sample taken in-situ. Better knowledge of the physical properties of a whole object and its material properties would then allow a better optimization of mitigation strategies. Marco Polo can provide a significant contribution in this field. We can only hope that not only Marco Polo, but also other sample return missions will be programmed by space agencies, as there is a wide diversity of bodies in the NEO population, and several missions will be required to achieve a representative knowledge and to define suitable strategies for each type.

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